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PERFORMANCE EFFECT OF FULLY SHROUDING A CENTRIFUGAL SUPERCHARGER IMPELLER

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ADVANCE RESTRICTED REPORT

PERFORMANCE EFFECT OF FULLY SHROUDING A CENTRIFUGAL SUPERCHARGER IMPELLER

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SUMMARY

A program of tests was conducted to determine the effect of an integral front shroud on the performance characteristics of a centrifugal supercharger impeller. The impellers tested were a modification of a commercial semishrouded impeller and a fully shrouded impeller, which was the same as the semishrouded one except for an integral front shroud. Tests were conducted in a variable component test setup in conjunction with a vaneless diffuser of NACA design at impeller tip speeds from 800 to 1200 feet per second.

Results of the tests indicated that the peak performance of the fully shrouded impeller occurred at a larger flow quantity than that of the semishrouded impeller and that the performance characteristics of the fully shrouded impeller were slightly better than those of the corresponding semishrouded impeller at tip speeds of 800 and 900 feet per second. This advantage decreased with an increase in tip speed and, at tip speeds of 1000 feet per second and above, the performance of the semishrouded impeller was better. Results indicated that fully shrouding an impeller of the type tested does not result in any significant improvement in performance.

INTRODUCTION

The superior performance of a fully shrouded centrifugal supercharger impeller, in which the air passages are completely contained within the body of the impeller, has been a controversial question. This type of impeller has been used in relatively few instances, although certain fundamental advantages, such as a reduction of axial thrust and an elimination of the losses that normally occur as a result of interpassage flow through the impeller clearance space,

have been claimed for it. The presence of an integral front shroud, although it does reduce the bursting strength of the impeller, makes the structure stiffer and less subject to vibrational failure.

Reports giving performance characteristics of experimental and commercial fully shrouded impellers have been published, in which claims of superiority have been made for fully shrouded impellers. (See references 1, 2, and 3.) Although some of these impellers had outstanding performance, it was not established that the integral front shroud of the impeller was the primary contributing factor. One impeller, which has created widespread interest and for which a number of claims have been made, was developed by the Deutsche Versuchsanstalt für Luftfahrt (DVL). Published results by Werner von der Nüll have claimed that the DVL fully shrouded impeller has an advantage of as much as 5 points in adiabatic efficiency over an equivalent semishrouded impeller (references 1 and 2); that the shrouded impeller has better performance throughout the operating range (reference 2); and that an adiabatic efficiency of over 80 percent was obtained for a supercharger using this impeller (references 1 and 2).

Kollmann (reference 3) states that the DVL fully shrouded impeller is better than semishrouded impellers only at low tip speeds. The NACA tested a DVL supercharger incorporating a fully shrouded impeller (reference 4) and obtained performance about equal to the most efficient production-type American superchargers. The Bristol Aeroplane Company Limited of England manufactures superchargers with fully shrouded impellers, but unpublished results of tests of one of these impellers by the NACA indicated no performance advantage over more conventional types of impeller.

This report presents the results of an investigation to isolate the effect of an integral front shroud on the performance of one type of centrifugal supercharger impeller. The method chosen for this investigation was to construct a fully shrouded impeller that was designed to copy the passages of a production-type semishrouded impeller which had good performance. This method, though requiring great machining complexity, had the advantage of establishing the possible improvement resulting from the addition of a shroud to an impeller that was considered good rather than finding the loss which might result from removing the shroud from a fully shrouded impeller proportioned for ease of machining. The performance characteristics of the fully shrouded impeller and the corresponding semishrouded impeller were compared at impeller tip speeds from 800 to 1200 feet per second. The performance tests were started at the NACA Langley Field laboratory and completed at Cleveland.

IMPELLERS

A fully shrouded impeller was designed to copy the passages of an existing conventional radial impeller that was considered to have good performance characteristics. Because it was not mechanically feasible to machine a fully shrouded inlet section, the fully shrouded impeller was constructed with a separate inducer that had no front shroud. In order to make the semishrouded impeller directly comparable, a conventional impeller was modified by adding a similar separate inducer.

Fully Shrouded Impeller

A commercial semishrouded impeller of conventional type (fig. 1) was used as the basis for the design of the fully shrouded impeller. It is a 12-inch diameter semishrouded wheel, with 22 radial blades, and with scallops around the impeller periphery. The fully shrouded impeller was designed to have the same passage profiles as this conventional semishrouded impeller, and the passage fillets and the constant-thickness blades were proportioned to maintain the same passage areas as this basic impeller. The scallops were omitted on the fully shrouded impeller. Bending of the inlet blades was structurally impracticable on the fully shrouded impeller, and it was necessary to use a separate inducer in conjunction with this impeller. This separate inducer section, which copied the bending of the semishrouded impeller inlet section, was mounted on the front face of the fully shrouded impeller (fig. 2). Because the fully shrouded impeller proper was of the same depth as the conventional semishrouded impeller, the addition of the inducer resulted in a longer flow path for the fully shrouded impeller, as well as in differing passage-area characteristics in the region of bending.

Another functional difference resulted from the fact that the separate inducer had a constant hub diameter and a constant outside diameter, whereas the inlet section on the conventional semishrouded impeller had an increasing radius along the axial depth. Compression in a centrifugal supercharger is accomplished by increasing the moment of momentum of the air by means of an increase in angular velocity and an increase in radius of rotation of the air as it flows through the impeller. In the impeller with a separate inducer, the angular velocity is theoretically imparted to the air before the radius of rotation is increased, whereas in the inlet section of the conventional semishrouded impeller, these two functions are partly superimposed.

The impeller front shroud was designed as a compromise between a design that would approach the elastic strain of the impeller disk and blades and a shroud that would not stress the blades at the entrance too highly. Similar elongation for the front shroud and the rear disk would reduce the load transference, which is the source of additional and complex stresses. The elongation of the impeller disk and blades was computed along the radius by a modification of the stress-function method given in reference 5. A series of hyperbolas was used to define the rear-shroud profile, and the impeller-blade load was considered as a density variation in the rear-shroud disk. The impeller front shroud was then computed on the basis of the two opposing requirements and the compromise made. The inducer section, because it constituted a weaker structure than the inlet section of the basic impeller, was analyzed on the basis of strength. Centrifugal stresses calculated for the inducer were lower than the maximum calculated stresses in the impeller disk.

The fully shrouded impeller was machined by the NACA Langley Field machine shop from a solid aluminum forging. The inducer was fabricated by machining straight blades and forming them to the required contour with special bending dies. The inducer was fitted to the impeller by machining the inducer blades to match corresponding notches in the impeller blades. When assembled with a pinch fit, this mounting arrangement assured alinement of the blades and provided support for the inducer blades.

Modified Semishrouded Impeller

A semishrouded impeller, the same as the fully shrouded impeller except for the front shroud, was obtained by modifying an unfinished model of the basic semishrouded impeller. This modification was accomplished by mounting a separate inducer on the front of a basic impeller on which the inlet blades had not been bent or beveled. The inducer was the same as the fully shrouded impeller inlet section, except that the blades were radially tapered rather than of uniform thickness at the impeller entrance. This modified semishrouded impeller was then equivalent, in passage form, to the fully shrouded impeller, and comparative tests would give a valid indication of the effect of a front shroud on performance.

The modified semishrouded impeller with the added inducer is shown in figure 3. The inducer section was made by the method used in constructing the inducer for the fully shrouded impeller.

APPARATUS AND TESTS

Test Setup

The test installation at the Langley Field laboratory was made in a variable component supercharger test setup that incorporated a vaneless diffuser. The installation was made in accordance with reference 6, except that only one radial outlet pipe was used because of space limitations. Previous tests had shown no appreciable difference in performance when one outlet pipe was used instead of two.

When the test setup was reinstalled at the Cleveland laboratory, the single discharge pipe was retained to make the installations comparable. The two installations were the same except that, in the Langley Field test unit, the outlet pipe discharged through a duct system directly to the atmosphere, whereas in the Cleveland laboratory setup, the outlet pipe discharged into the laboratory atmospheric-exhaust system in which the pressure was maintained at 3 inches of water below atmospheric pressure.

The impellers were tested in conjunction with a vaneless diffuser of NACA design and construction. This vaneless diffuser has an outside diameter of 34 inches and a passage-area divergence (equivalent to a cone with an apex angle of 6° lying along the ideal logarithmic spiral flow path for rated flow) that was found to give a flat performance curve in previous impeller tests. A vaneless diffuser was used in the tests because it has uniform operating characteristics over a wide range of air flows and is less subject to small changes in impeller characteristics than a vaned diffuser, thereby giving a more valid comparison of the characteristics of the impellers. Schematic diagrams of the installations of the fully shrouded impeller and the modified semishrouded impeller in conjunction with the vaneless diffuser are shown in figure 4.

Instrumentation

The location of the standard instruments and the precision of instrumentation was as prescribed in reference 7, except that the inlet measuring station was at 4 instead of 2 pipe diameters from the impeller-inlet plane. Total-pressure survey tubes were provided in the diffuser, with the four tubes located at diameters of 13, 16, 23, and 33 inches. The total-pressure survey tubes were of 3/32-inch diameter with a 1/32-inch-diameter hole drilled in the side of the tube near the plugged end for measuring the pressure. Survey pressure readings were accurate to ±0.1 inch of mercury.

Tests

Tests of the fully shrouded impeller and the conventional semishrouded impeller were conducted at the NACA Langley Field laboratory and tests of the modified semishrouded impeller were made at the NACA Cleveland laboratory. In addition, tests of the conventional semishrouded impeller were repeated in the second test installation at the Cleveland laboratory to check the reproducibility of the test results. Reproduction of the data was satisfactory, with peak efficiency checking within ±0.5 percent at all speeds.

The tests of the fully shrouded impeller and the modified semishrouded impeller were conducted to determine the effect of an integral impeller front shroud on impeller performance. Results of tests of the conventional impeller were used only to determine the effect of the use of a separate inducer on the performance of the semishrouded impeller.

Over-all tests of the three impellers were conducted in accordance with reference 7 at tip speeds from 800 to 1200 feet per second. In the Langley Field installation, however, the limited capacity of the discharge system restricted flow to the extent that outlet pressures were above 40 inches of mercury absolute with wide-open throttle. The maximum flow values attained in the tests of the fully shrouded impeller and the conventional semishrouded impeller are therefore not directly comparable with the tests of the modified semishrouded impeller, in which this effect was not present. Minimum-flow values in all tests represented the incipient surge point of the unit at each speed. Tests were conducted with inlet air of room temperature.

Surveys at the diffuser stations were taken in conjunction with the over-all tests. A total-pressure survey with a given tube consisted in rotating the tube until a maximum reading was obtained at the midpoint of each of four equal lengths across the diffuser passage.

Computations

Computations of over-all characteristics, including adiabatic efficiency η_{ad}, pressure coefficient q_{ad}, and load coefficient Q_1/n, were made in accordance with reference 7. The values of η_{ad} at the diffuser stations were computed using the total-pressure readings of the diffuser surveys and the total temperature as determined in the outlet pipe. The average total pressure at any diffuser

station was obtained by arithmetically averaging the pressures obtained across the diffuser passage. Check computations for a number of test conditions verified the fact that the difference between an arithmetic average and a mass-flow average was negligible. It was assumed that there was no heat transfer in the lagged installation, and therefore the total temperature in the diffuser was taken as equal to that at the outlet measuring station.

RESULTS AND DISCUSSION

Effect of Semishrouded Impeller Modification

Comparison of the characteristics of the conventional semishrouded impeller with those of the modified semishrouded impeller (fig. 5) shows the effect of the modification on the performance of the basic impeller. At tip speeds up to 1000 feet per second, the addition of the separate inducer had little effect on the performance of the semishrouded impeller. In this speed range, the characteristic curves seemed to indicate that the modified semishrouded impeller had a greater range than the conventional impeller. The apparent advantage in maximum load coefficient, however, was due to the difference in test-rig installations. As previously discussed, the small capacity of the discharge system in the Langley Field installation limited the maximum flow in the tests of the conventional semishrouded impeller.

At tip speeds of 1100 and 1200 feet per second, the modified impeller had unstable flow characteristics and an irregular performance curve, whereas the conventional impeller had a relatively flat characteristic curve. The instability of flow with the modified semishrouded impeller was probably the result of the inlet-blade form and the uncontrolled passage divergence.

In general, except for the instability of operation at tip speeds of 1100 and 1200 feet per second, the effect of the modification on the performance characteristics of the semishrouded impeller was small. This small change in performance indicated that comparative tests of the modified semishrouded impeller and the fully shrouded impeller would establish the effect of an integral front shroud on the performance of a semishrouded impeller of conventional type.

Effect of the Impeller Front Shroud on Performance

Over-all performance characteristics of the modified semishrouded impeller and the fully shrouded impeller, in conjunction with a vaneless diffuser, were used as the basis of comparison for the two impellers. Performance based on total-pressure measurements at the impeller discharge and at stations throughout the diffuser showed that the test installation was suitable for showing impeller effects on the basis of over-all performance.

Over-all performance. - The over-all adiabatic efficiencies and pressure coefficients for the two impellers, tested in conjunction with the vaneless diffuser, are shown in figures 6 and 7, respectively. At impeller tip speeds from 800 to 1000 feet per second, the curves of adiabatic efficiency and pressure coefficient for the modified semishrouded impeller had a flat characteristic, peaking in a lower load-coefficient range than the fully shrouded impeller, with the result that the fully shrouded impeller had better performance in the upper load-coefficient range, and the semishrouded impeller had the advantage in the lower load-coefficient range. The range over which the fully shrouded impeller had better performance was a maximum at 800 feet per second, dropping with a speed increase until at 1000 feet per second the advantage existed only in the load-coefficient range from 0.31 to 0.37. The advantage in maximum load coefficient indicated for the semishrouded impeller was again due to the difference in test-rig installations.

At tip speeds of 1100 and 1200 feet per second, both the fully shrouded impeller and the modified semishrouded impeller had unstable flow characteristics. (See figs. 6 and 7.) This condition was especially true of the modified semishrouded impeller, which exhibited heavy pressure pulsations in the operating range. In general, at high tip speeds, the performance curves for the two impellers had similar characteristics, with flow pulsation affecting the performance of both.

Peak adiabatic efficiency, plotted over the range of tip speeds in figure 8, shows that the performance of the fully shrouded impeller was better than that of the semishrouded impeller at the low speeds; the advantage was 2.5 points at a tip speed of 800 feet per second and 1.0 point at 900 feet per second. The semishrouded impeller performance was better at speeds of 1000 feet per second and above, with a maximum advantage of 4.0 points at 1100 feet per second. This trend of the fully shrouded impeller to have an advantage only at low tip speeds is in general agreement with the results published in reference 3. The peak efficiency of the fully shrouded impeller

decreased rapidly with an increase in speed, whereas the peak efficiency of the semishrouded impeller had a slower decline up to 1100 feet per second and a sudden drop at 1200 feet per second. At 1200 feet per second, there was little difference in the characteristics of the impellers, probably the result of the unstable flow characteristics of each impeller.

Performance based on diffuser surveys. - The adiabatic efficiencies determined from total-pressure measurements in the diffuser are shown in figure 9 for tip speeds of 800, 1000, and 1200 feet per second. These curves indicate the same relative performance characteristics for the fully shrouded impeller and the modified semishrouded impeller as do the curves of over-all efficiency. Because of the fundamental difficulty of obtaining precise measurements in turbulent flow, the absolute values of efficiency may be in error especially in the region of the impeller tip; however, the curves do indicate the relative merits of the two impellers and substantiate the over-all efficiency results.

At a tip speed of 800 feet per second (fig. 9(a)) the fully shrouded impeller operated at a higher efficiency than the semishrouded impeller over nearly the entire range. The relative impeller characteristics, as established at the 13-inch-diameter station were maintained throughout the entire diffuser and in the outlet pipe.

At a tip speed of 1000 feet per second (fig. 9(b)) the efficiency curves for the fully shrouded impeller and the semishrouded impeller, as established at the diffuser stations, had the same relative characteristics as the curves of over-all efficiency. There was a slight shift in the relative positions of the curves from the impeller tip to the 23-inch station, but the readings at the 23-inch and 33-inch diameter stations gave efficiency curves of the same form as those in the outlet pipe.

The comparison curves at a tip speed of 1200 feet per second (fig. 9(c)) were rather incomplete as a result of the pressure pulsations that occurred in the operating range of the modified semishrouded impeller. As shown in figure 9(c), surveys in the diffuser were unobtainable in the mild pressure pulsation range, although flow in the discharge duct was sufficiently stabilized to determine over-all characteristics. The points that were obtainable, however, indicated that the conclusions reached from the over-all performance curves were valid.

In general, the trends established in these diffuser surveys correlated with the corresponding over-all performance characteristics, justified the choice of a vaneless diffuser for the comparative tests, and indicated that the characteristics determined from outlet-pipe measurements were adequate to establish the relative merits of the two impellers and determine the effect of an impeller front shroud.

SUMMARY OF RESULTS

Comparative tests of a semishrouded impeller of conventional type and the corresponding fully shrouded impeller established the following results:

1. The presence of a front shroud shifted the range of peak performance to a higher load coefficient.

2. The performance of the fully shrouded impeller was better than that of the corresponding semishrouded impeller over most of the load-coefficient range at tip speeds of 800 and 900 feet per second. The range over which the fully shrouded impeller had the advantage decreased with speed; and at tip speeds of 1000 feet per second and above, the semishrouded impeller had the advantage over most of the flow range.

3. The presence of the front shroud increased the peak over-all efficiency by 2.5 points at 800 feet per second and 1.0 point at 900 feet per second, with the semishrouded impeller having the advantage at tip speeds of 1000 feet per second and above. The maximum advantage of the semishrouded impeller was 4.0 points at 1100 feet per second.

CONCLUSION

Fully shrouding a conventional centrifugal supercharger impeller of the type tested does not result in any significant improvement in performance characteristics.

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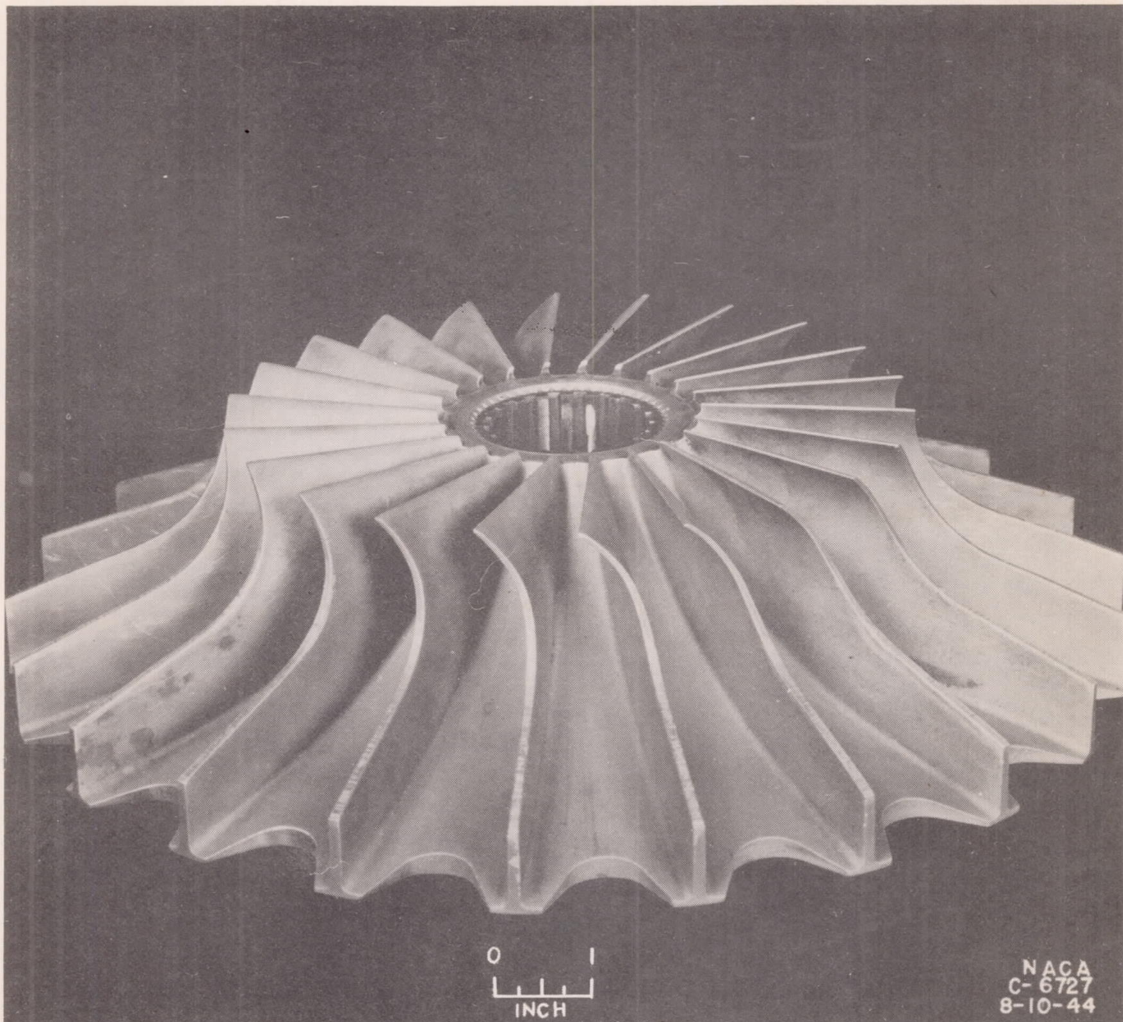

Figure 1. - Conventional semishrouded impeller.

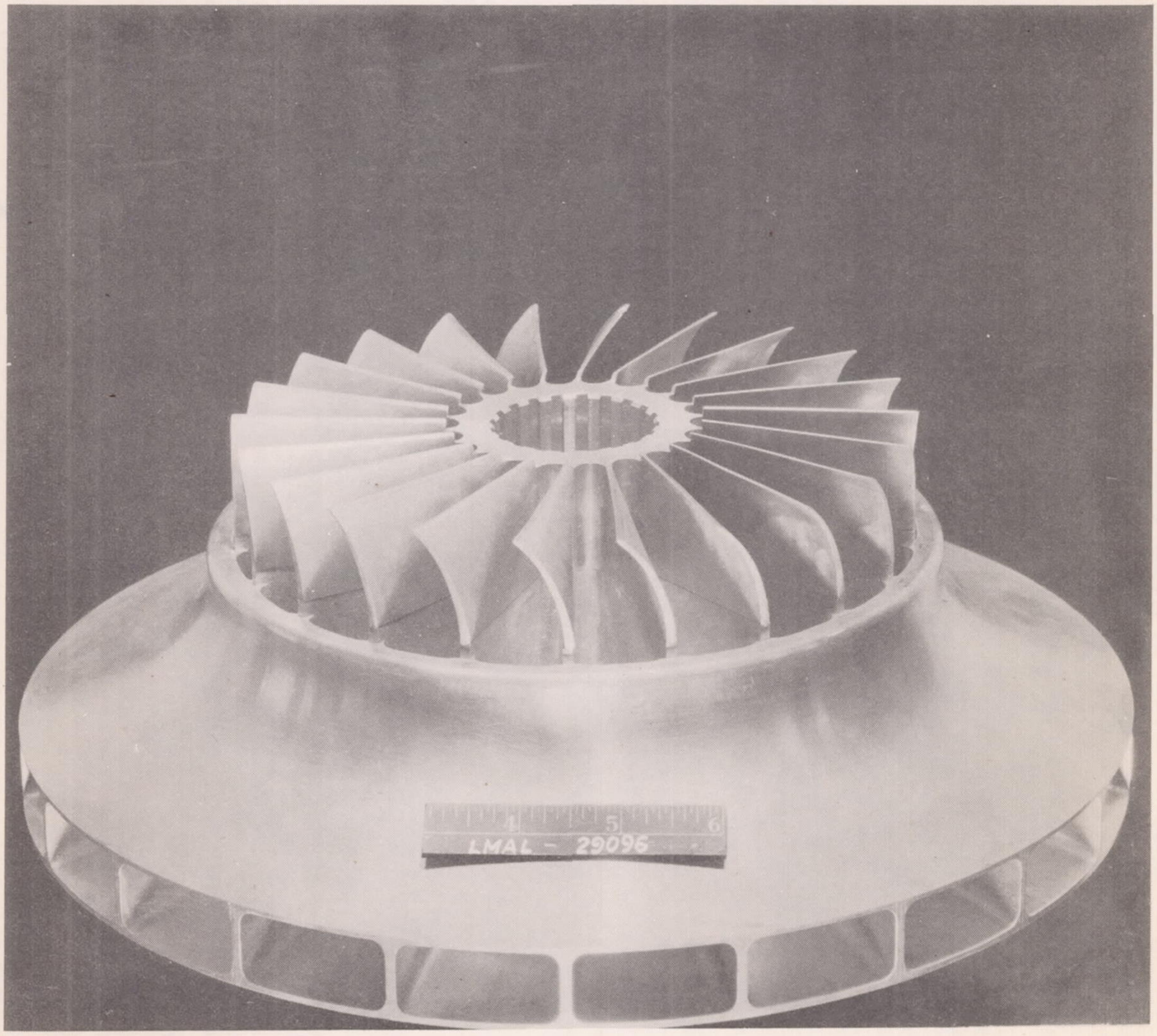

Figure 2. - Fully shrouded impeller.

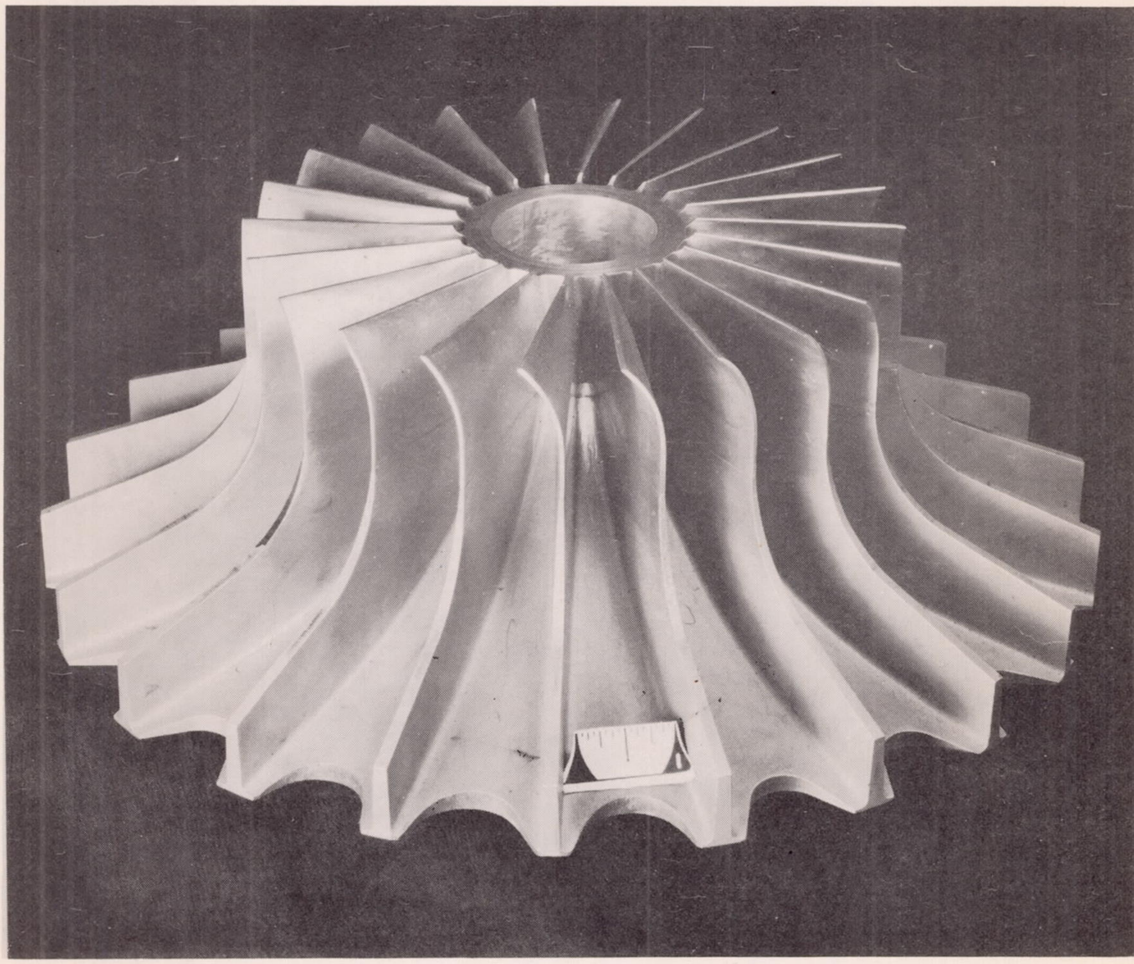

Figure 3. - Modified semishrouded impeller.

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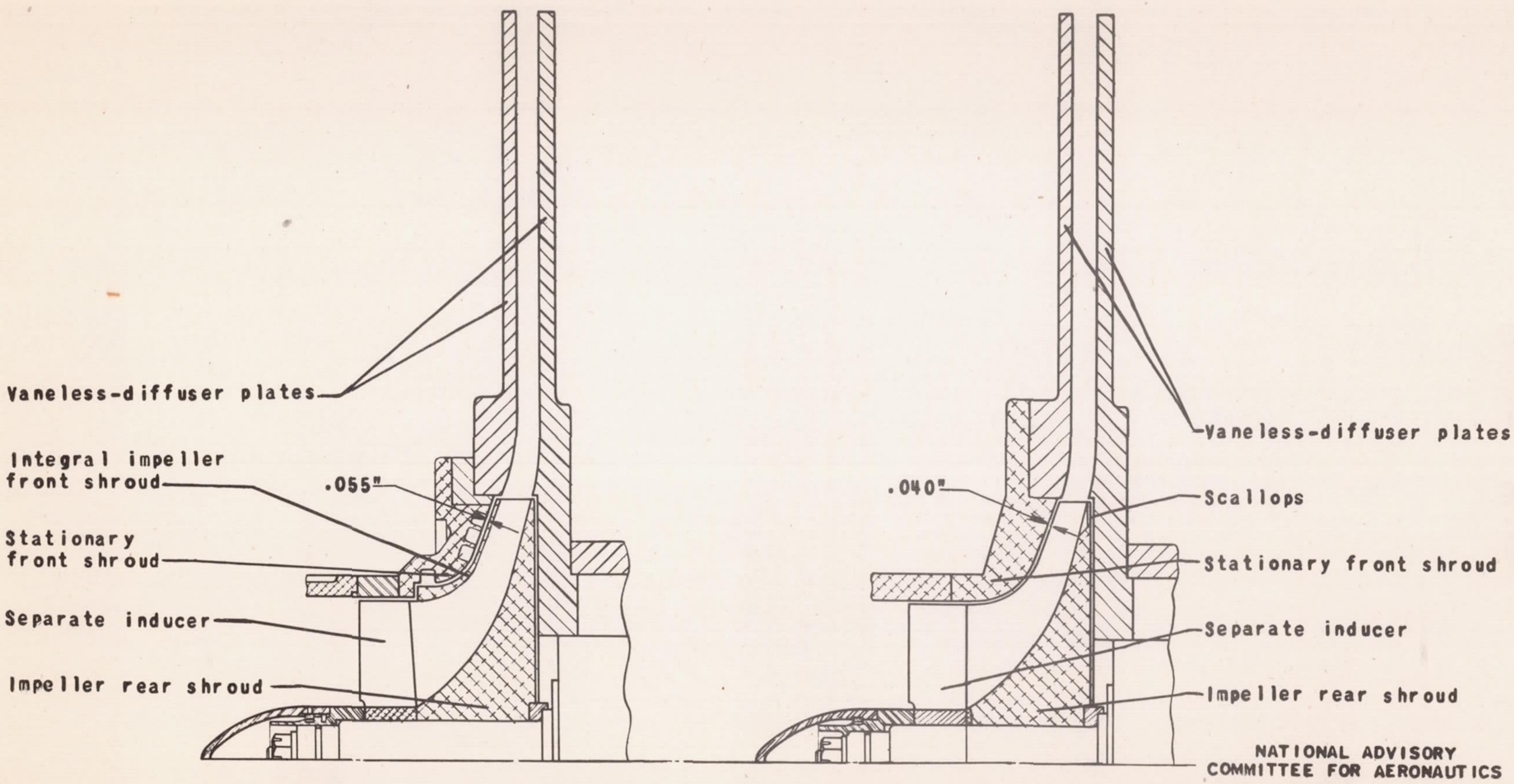


(a) Fully shrouded impeller. (b) Modified semishrouded impeller.

Figure 4. - Installation of fully shrouded and modified semishrouded impellers.

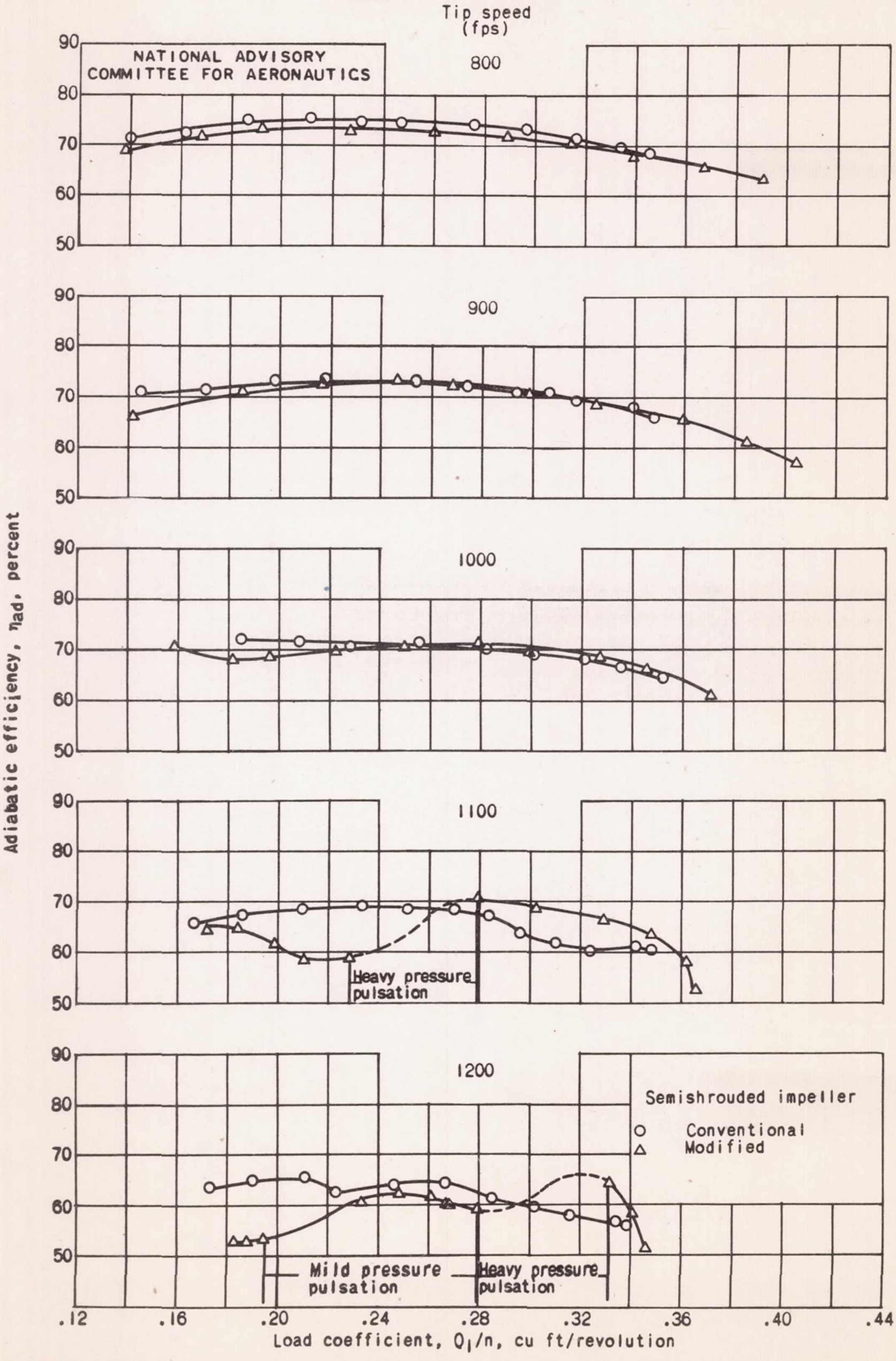


Figure 5. - Comparison of over-all adiabatic efficiency of conventional semishrouded impeller and modified semishrouded impeller.

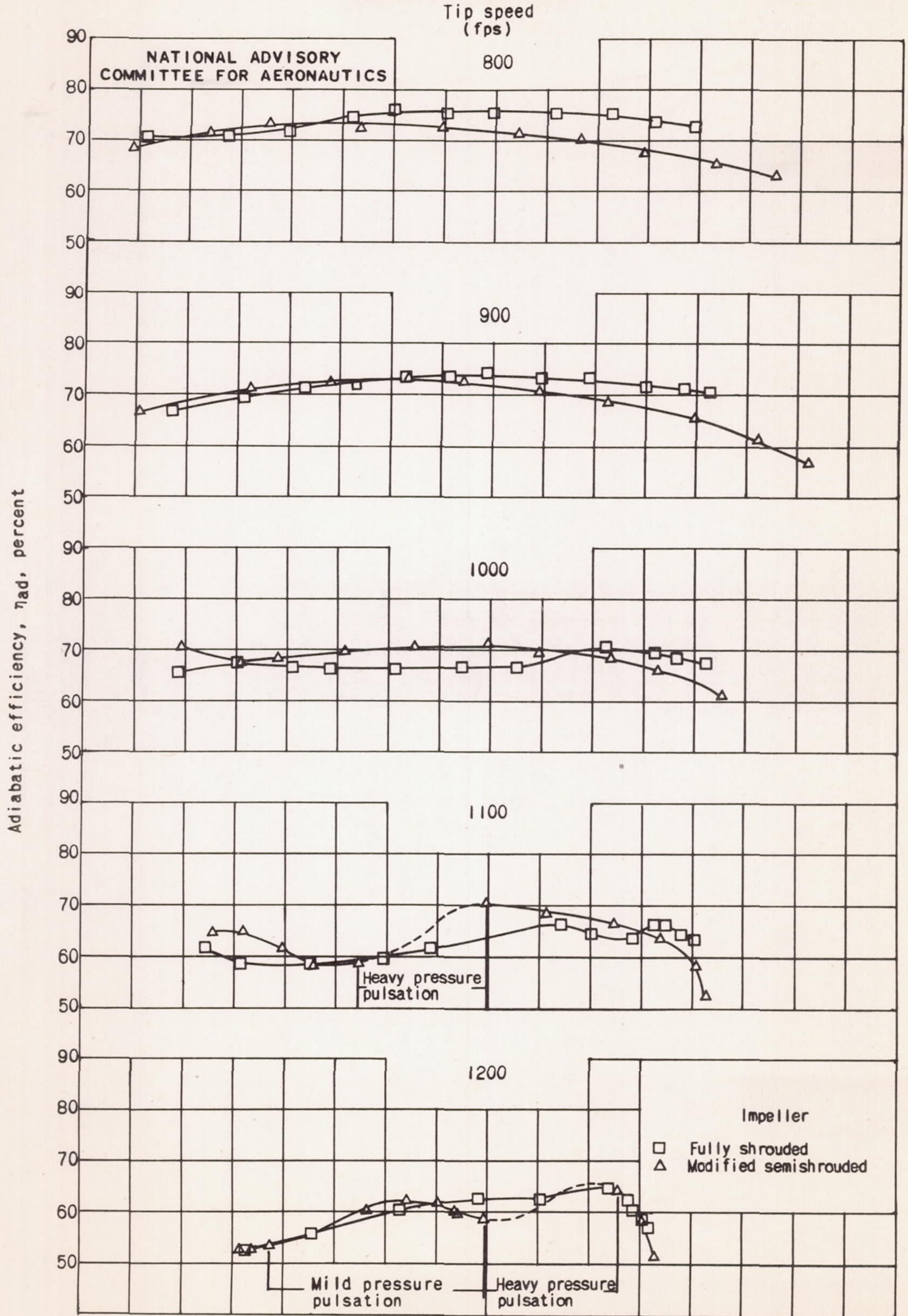


Figure 6. - Comparison of over-all adiabatic efficiencies of fully shrouded impeller and modified semishrouded impeller.

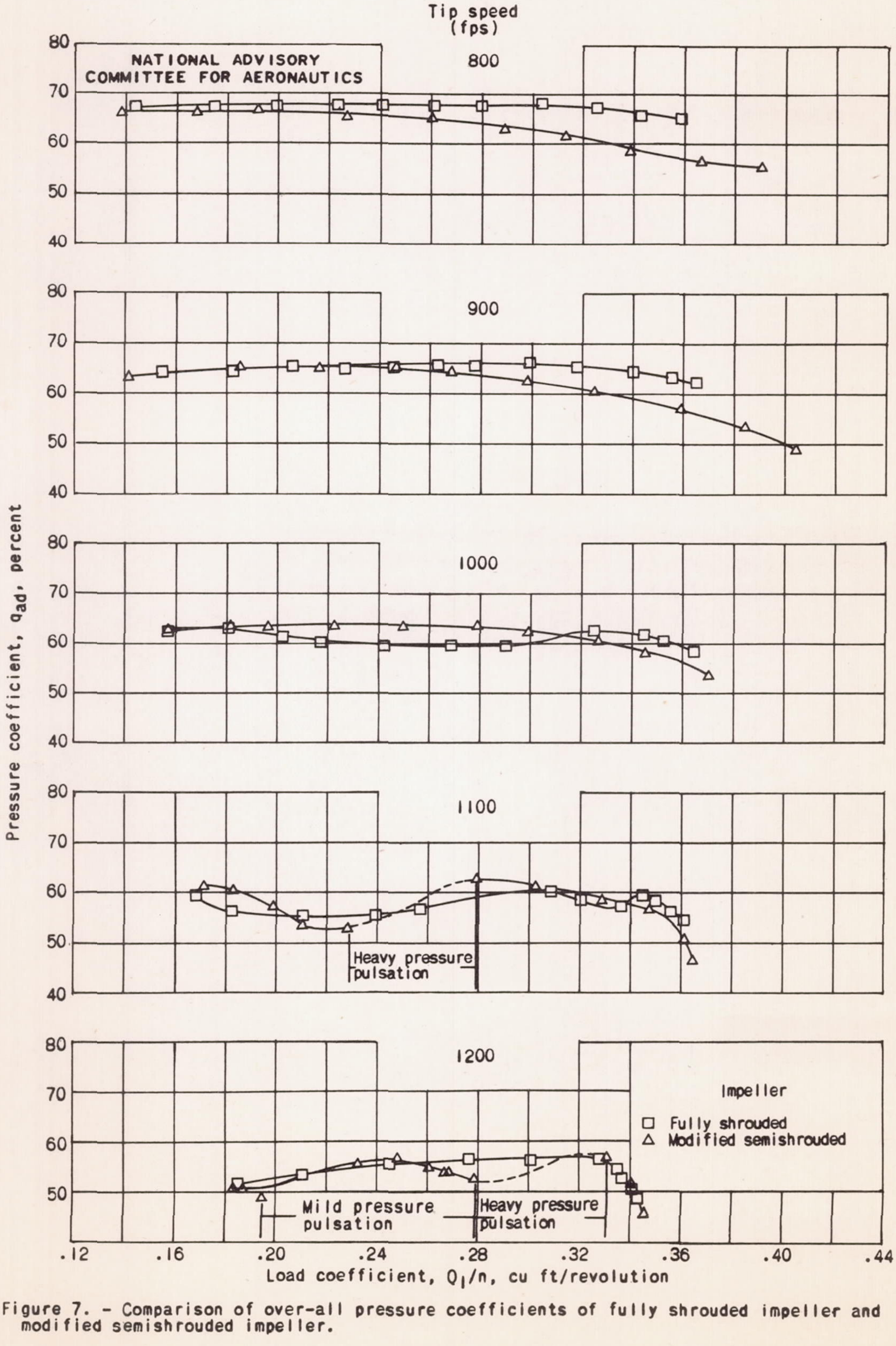


Figure 7. - Comparison of over-all pressure coefficients of fully shrouded impeller and modified semishrouded impeller.

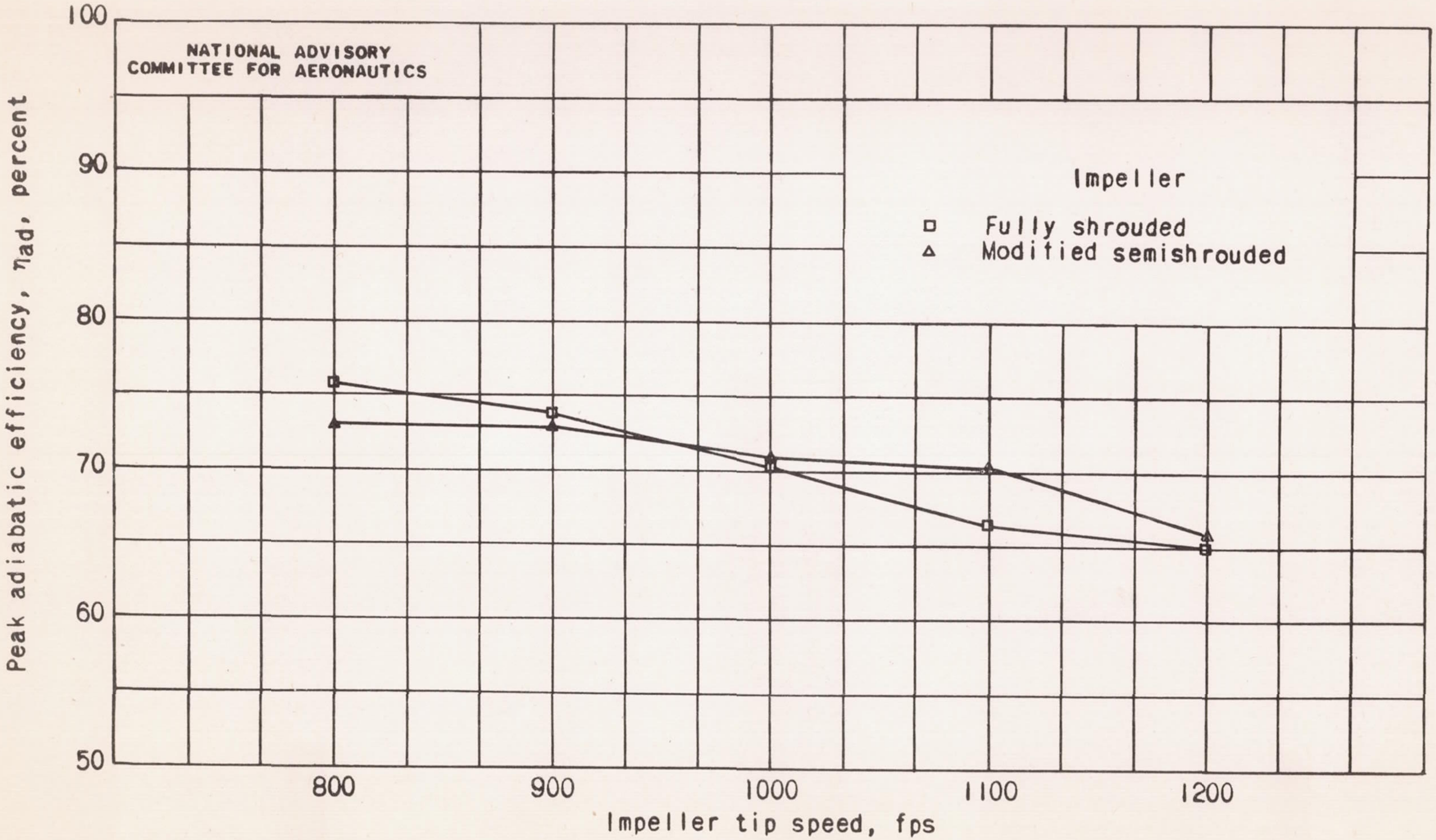
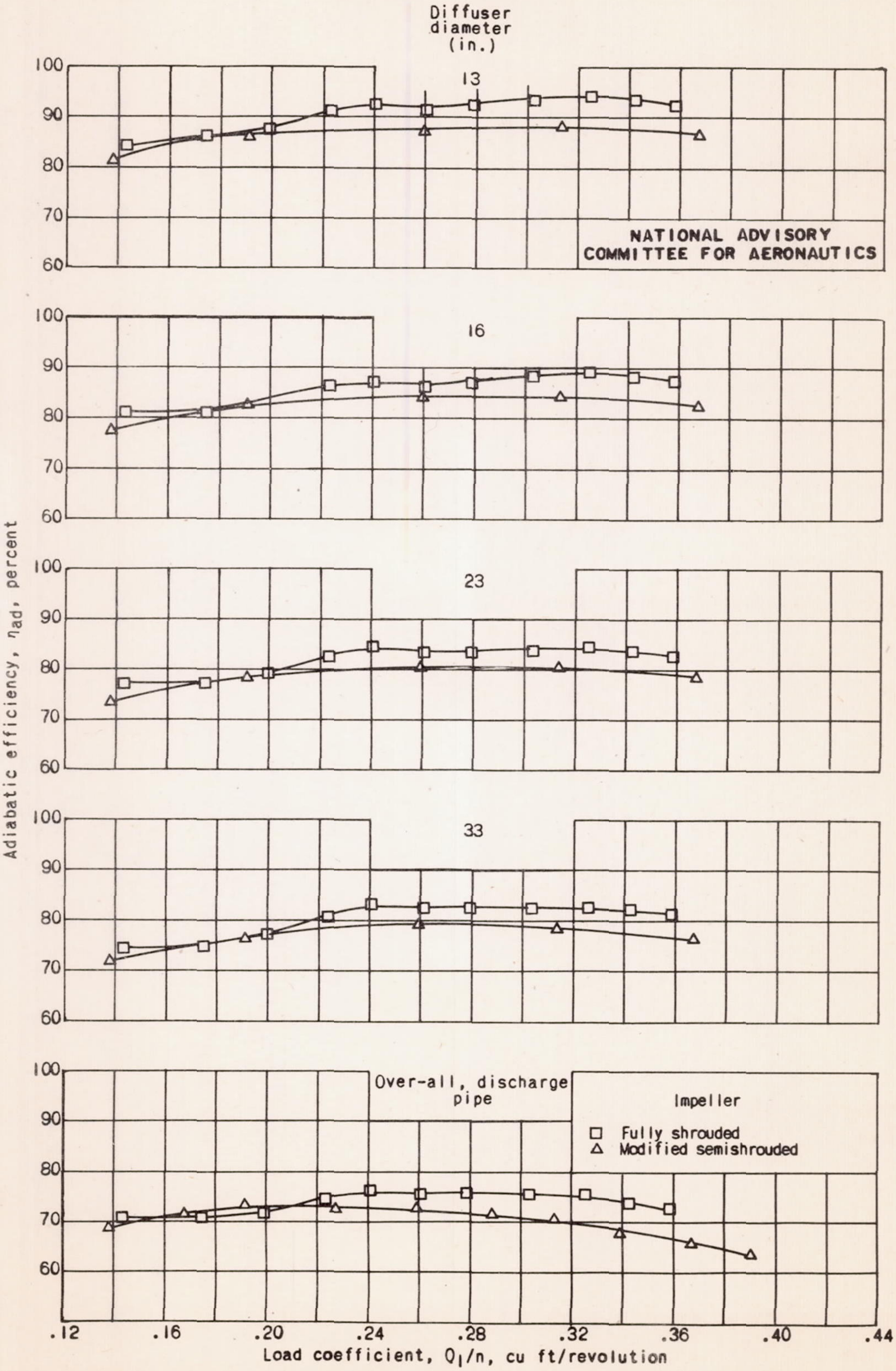
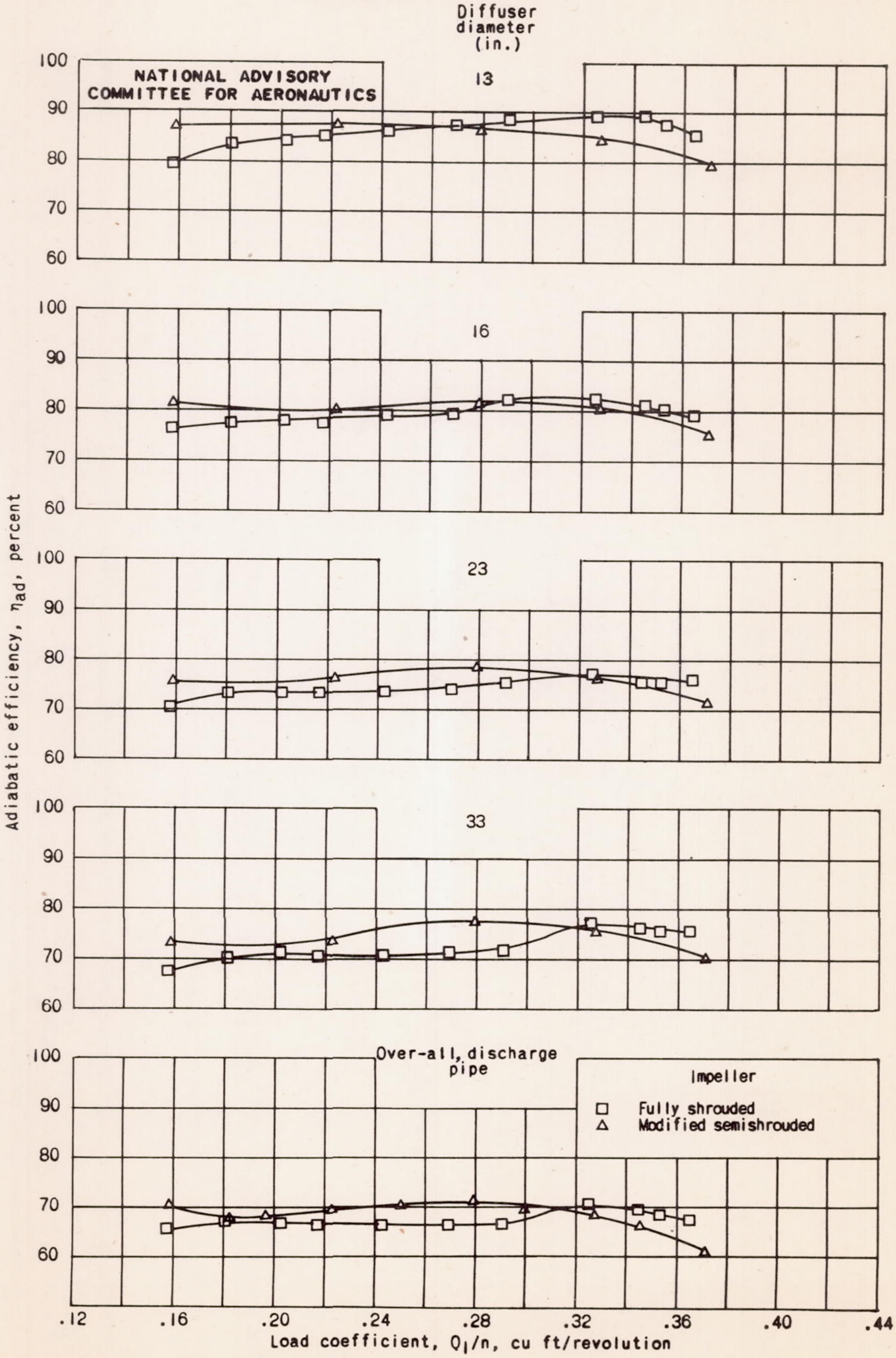


Figure 8. - Comparison of peak over-all adiabatic efficiencies of fully shrouded impeller and modified semishrouded impeller.



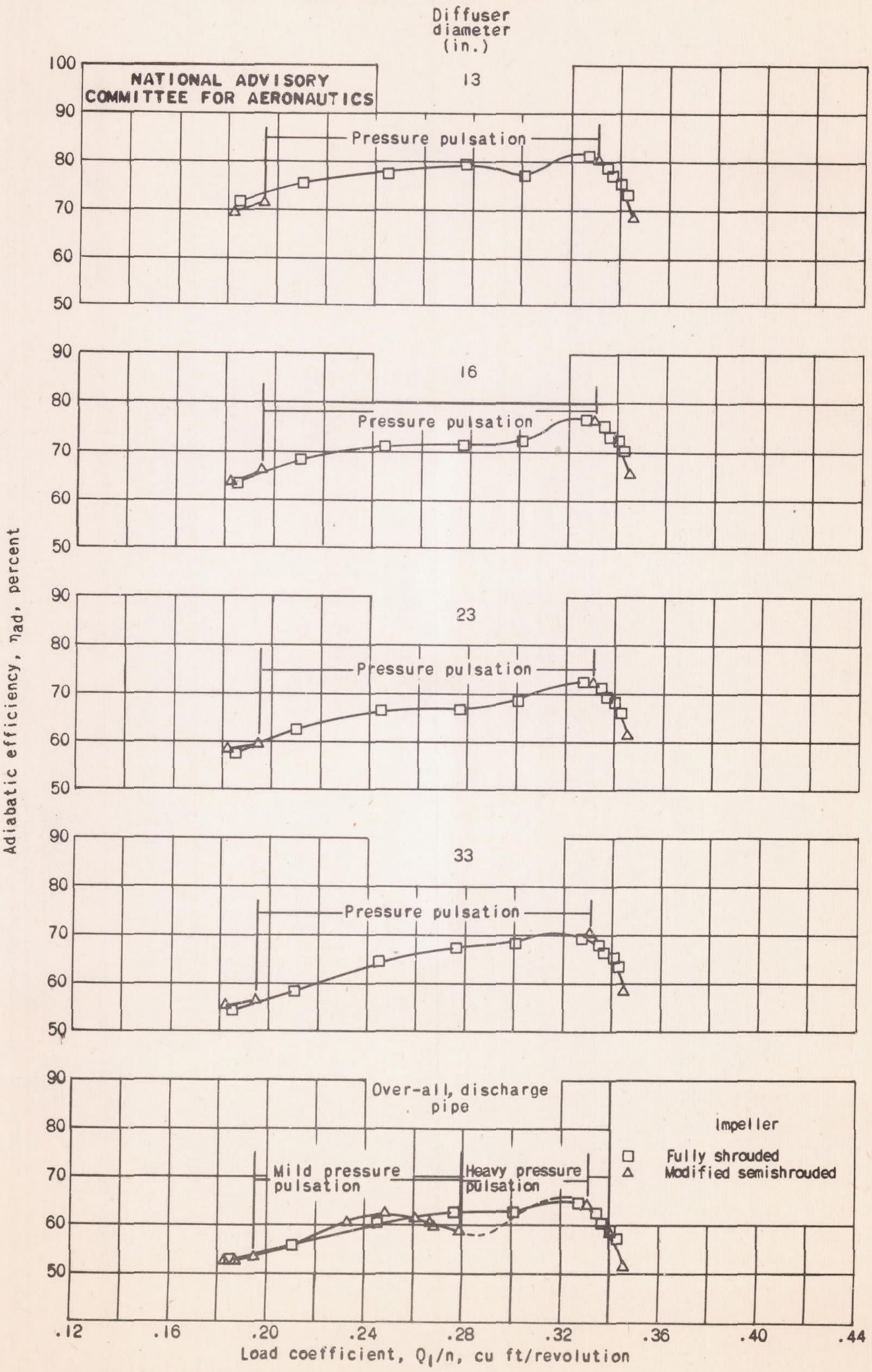
(a) Tip speed, 800 feet per second.

Figure 9. - Comparison of adiabatic efficiencies of fully shrouded impeller and modified semishrouded impeller at various measuring stations.



(b) Tip speed, 1000 feet per second.

Figure 9. - Continued.



(c) Tip speed, 1200 feet per second.

Figure 9. - Concluded.